NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4316

FRICTION AND WEAR WITH REACTIVE GASES AT TEMPERATURES UP TO 1200° F

By Gordon P. Allen, Donald H. Buckley, and Robert L. Johnson

Lewis Flight Propulsion Laboratory
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SUMMARY

Friction and wear experiments were conducted to explore the effects of high temperature, varied chlorine content, sulfur catalysis, and preformation of sulfide films on boundary lubrication with reactive gases. Dichlorodifluoromethane (CF_2Cl_2), chlorotrifluoromethane (CF_3Cl), and sulfur hexafluoride (SF_6) gases were used to lubricate M-1 tool steel riders sliding on M-1 tool-steel disks at temperatures up to 1200° F. A 3/16-inch-radius hemisphere rider under a load of 1200 grams contacted the flat surface of a rotating disk; the usual surface speed was 120 feet per minute. In some cases, alloys other than M-1 tool steel were used for the rider specimen.

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CF_2Cl_2 was more effective than CF_3Cl as a lubricant at all temperatures. The addition of small amounts of SF_6 to the gases improved lubrication. The SF_6 was considered to act as a catalyst to improve the chloride reaction at the slider interface. Sulfur hexafluoride alone is capable of giving reduced wear but does not reduce friction significantly for tool steel. Pretreatment by sulfurizing caused wear reduction both in air and in SF_6. At 600° F, nickel alloys that contained substantial silicon and were lubricated with SF_6 gave low friction and wear with negligible corrosion. Of the iron, copper, and nickel alloys studied, the silicon-nickel alloys gave the best results. Corrosion is a very important problem with tool steel operating at high temperatures in these gases.

INTRODUCTION

The maximum temperatures anticipated in lubrication systems of future aircraft propulsion devices (up to approximately 1000° F) are beyond those limiting the usefulness of the usual types of organic liquids and grease lubricants. Lubricants, such as high-molecular-weight aromatic compounds, solid lubricants, and hydrostatic gas films (e.g., pressurized air), as well as the reactive gases (halogenated methane compounds), are being considered for high-temperature lubrication problems (refs. 1 to 5).

With regard to the potential use of reactive gases, thermal stability is one of the more important considerations. Several gases, such as dichlorodifluoromethane, are stable in contact with steel at 1000° F ambient temperature. During sliding contact, however, the flash temperatures at the contacting asperities are extremely high (refs. 6 and 7). These surface temperatures can be sufficiently higher than the ambient so that chemical bonds of the adsorbed gas molecules on the surface are ruptured. Labile atoms of reactive elements, such as chlorine, are released from the gas molecule and subsequently react at the hot spots with the metal sliding surface. With steel surfaces, iron chlorides have been identified as the reaction products (ref. 5); these iron chlorides will function as solid lubricants and be reformed where needed. This mechanism is fundamentally the same as that for "extreme pressure" lubrication by reactive compounds, such as additives in gear oils described in references 8 to 10. Similar reaction films are reported also in reference 11, where solid-lubricant films were obtained by heating in gases prior to operation.

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Previous NACA research studies on lubrication with reactive gases (refs. 5 and 12) were made mostly at room temperatures; yet the importance of corrosion was very apparent. One way of minimizing the corrosion problem is to reduce the amount of chlorine in the gas molecule. Previous data (ref. 5) obtained at room temperature showed, however, that molecules containing two or more chlorine atoms were required for effective lubrication (at room temperature). Increasing the ambient temperature may make it possible to obtain an adequate surface reaction for effective lubrication with only one atom of chlorine per molecule. Further, reference 10 indicates that the metal surface reactions with chlorine-type additives in liquids were catalyzed by the presence of sulfur compounds. Mixtures of gases also might function in this manner. For example, a gas containing less chlorine per molecule, such as chlorotrifluoromethane, might be mixed with a sulfur-containing gas, such as sulfur hexafluoride, to obtain surface reactions adequate for effective lubrication. Sulfur hexafluoride is of interest because it has good thermal stability.

The object of the research reported herein was to explore the influence of broad temperature ranges, sulfur catalysis, preformation of sulfide films, and varied chlorine content on boundary lubrication of steel surfaces with reactive gases. The gases used were dichlorodifluoromethane (CF_2Cl_2), chlorotrifluoromethane (CF_3Cl), and sulfur hexafluoride (SF_6). Experiments were usually run with hardened M-1 tool-steel rider and disk specimens sliding together in an atmosphere of the reactive gas.

The ambient temperatures were varied from 75° up to 1200° F. Several other alloys including some with good corrosion resistance were also studied. Friction, wear, surface failure, and corrosion characteristics were noted. A 3/16-inch-radius hemisphere rider under a 1200-gram load contacted the flat surface of a disk rotating to give a sliding velocity of 120 feet per minute.

APPARATUS AND PROCEDURE

The apparatus used in this investigation is described in detail in reference 13 and is shown schematically in figure 1. The basic elements of the apparatus consist of a rotating-disk specimen (M-1 tool steel, $2\frac{1}{2}$-in. diam.) and a hemispherically tipped rider specimen (various materials, 3/16-in. rad.).

The rider specimen is stationary and is in sliding contact with the rotating-disk specimen. The disk was rotated by means of an electric motor coupled to a variable-speed transmission. Loads were applied to the rider specimen by means of a dead-weight system. The frictional force was measured directly by means of four strain gages mounted on a copper-beryllium dynamometer ring. The frictional force was continuously recorded on a strip-chart potentiometer. Wear was determined by measuring the diameter of the wear area on the rider specimen after the experiment; the wear volume was calculated.

The gaseous lubricants were introduced into a 2-liter Inconel pot that (with its cover) enclosed the disk and rider specimens. The Inconel pot was heated by means of strip heaters that were mounted on the outer walls and concentric-ring heaters that were contained in the base of the pot. The strip and ring heaters were controlled by individual Variac units. The temperature was measured by means of a stainless-steel-sheathed Chromel-Alumel thermocouple located along the side of the disk specimen, and the temperatures were read from an indicating potentiometer. The temperatures were varied from 75° to 1200° F.

The M-1 tool-steel disk specimens used were from the same heat and were hardened to Rockwell C-62. Several of these disks were sulfurized in accordance with reference 14. The rider materials used in addition to M-1 tool steel were: SAE 1020 steel, iron-silicon bronze, copper, beryllium-copper, H-monel, cast Inconel, Inconel X, G-nickel, $7\frac{1}{2}$ percent silicon-nickel, and arc-cast molybdenum.

Both rider and disk specimens were finish ground at 2 to 4 microinches. Before each run, the rider and disk were given the same preparatory treatment. This treatment consisted of four steps: First, a thorough rinsing with acetone to remove oil and grease from the surface; second, polishing with moist levigated alumina on a soft cloth; third, a thorough rinsing in tap water followed by distilled water; fourth, rinsing of the specimens with 95-percent ethyl alcohol and finally with acetone to remove any trace of water.

The gaseous lubricants used in this study were SF_6, CF_2Cl_2, and CF_3Cl. The physical and chemical properties of these gases can be found in references 15 and 16. Details on the system for transfer of gas to the test chamber are presented in reference 5. The Inconel pot was purged for a 20-minute period prior to the actual starting of the run. The gas flow rates and mixtures used in the purge were the same as those employed in the run. At the completion of the purge, the run-in procedure was initiated. Measurements reported in reference 5 show that less than 0.5 percent oxygen was present in the test chamber during operation with CF_2Cl_2.

The run-in was started with an initial surface speed of 55 feet per minute, and incremental loads of 200, 400, and 600 grams were applied in 1-minute intervals. A 1200-gram load was then applied for a period of 2 minutes, at the end of which time the surface speed was increased to 120 feet per minute. This speed was maintained for the duration of the 60-minute run.

The run-in procedure was found necessary as a result of some previous work with CF_2Cl_2 which showed that, if the run was started with high load and speed, surface failure of the specimens was apt to occur. High initial friction and wear can be attributed to the lack of sufficient time for the formation of a reaction film. As a result, it was found that, by reducing the speed and by incremental loading, a reaction film could form that markedly reduced the initial high friction and wear.

EXPERIMENTAL RESULTS

Data were obtained with M-1 tool-steel rider and disk specimens in air at 75° F and at 1000° F. The results in air (fig. 2) provide a basis for evaluating the lubricating effectiveness of the reactive gases under investigation. As expected from previous experience, the friction in air at 1000° F was significantly lower than that obtained at 75° F. Also, the wear was lower at 1000° F than at room temperature. These results at 1000° F show the beneficial influence that surface oxide films can have on friction and wear. Pretreatment by sulfurizing (ref. 14) to form a sulfide film had little beneficial effect in air (fig. 2). High-temperature wear was primarily abrasion with little if any evidence of metallic welding. Wear is dependent on the materials, lubricants, and conditions of operation; wear differences less than a factor of 2 are generally not significant.

Sulfur Hexafluoride

At 75° F, there was no significant difference in friction for untreated M-1 in air and sulfurized M-1 in air, as well as in SF_6. Untreated M-1 in SF_6, however, gave somewhat higher friction than untreated M-1 in air. No tendency for metallic welding to occur was observed during or after the run (erratic friction or stick-slip sliding can indicate welding during operation). At 75° F, both sulfurizing the specimens and operation in an atmosphere of SF_6 caused significant reductions in wear (fig. 2).

Operation at 1000° F gave lower wear and friction in each case than was observed at 75° F (fig. 2). Sulfur hexafluoride reduced both friction and wear for treated and untreated specimens at 1000° F. No evidence of surface failure was observed.

The data of figure 2 show that sulfide films can reduce wear appreciably. Sulfur hexafluoride was, therefore, considered as a possible gaseous lubricant as well as a catalytic agent for use with other gases. Results obtained to show the effect of varied temperatures with SF_6 as a lubricant are presented in figure 3. Friction coefficients were erratic but showed a decreasing trend as the temperature was increased from 75° to 1000° F. Data scatter (fig. 3) was extreme at temperatures from 400° to 800° F. Such scatter is unusual in the reactive-gas experiments. It is suggested that data scatter might be explained in terms of crystalline transformations. The various crystalline forms that might be obtained are indicated by the shaded area on the phase diagram of figure 4, which was adapted from reference 17. It must be appreciated, however, that the <u>exact</u> temperature and percentage of sulfur in the reaction film at the sliding interface are not known. Two primary crystalline transformations, with associated change in shear properties, occur in the temperature range where scatter was observed. These transformations are considered in more detail in the discussion to follow.

Figure 5 presents a photographic record of the appearance of a series of specimens after operation in SF_6 at various temperatures up to 1000° F. Sulfide films were obtained at temperatures of 600° F and higher; at 1000° F, objectionable scaling from corrosion was observed. M-1 tool steel is known to have relatively poor resistance to oxidation and other types of corrosion at high temperatures. The corrosion problem of concern is the bulk-surface chemical attack of the specimens and should not be confused with the surface reaction film formed by sliding contact on the wear areas.

The corrosion observed at elevated temperatures with M-1 tool steel in SF_6 suggested that other more corrosion-resistant metals should be considered. Friction-heat dissipation is more difficult for the rider specimen than for the disk because of continuous contact at the sliding interface of the rider. Thus, the operating temperature of the bulk of the rider specimen may be higher than the ambient and, therefore, the rider would be more subject to corrosion. Data were obtained with rider specimens of the following metals: SAE 1020 steel, iron-silicon-bronze, copper, beryllium-copper, H-monel, cast Inconel, Inconel-S, G-nickel, $7\frac{1}{2}$ percent silicon-nickel, and arc-cast molybdenum. The runs were made at 600° F because that was the temperature at which significant corrosion was first noted.

Figure 6 presents friction and wear data for the various rider materials run against M-1 tool steel in SF_6. G-nickel and $7\frac{1}{2}$ percent silicon-nickel gave very good results with respect to both friction (fig. 6(a)) and wear (fig. 6(b)). There was no evidence of corrosion of the nickel specimens during these experiments.

Dichlorodifluoromethane

The problem area for practical use of reactive gas lubricants is most apt to be at elevated temperatures (ref. 5). Therefore, the effects of varied and high temperatures on lubricating properties of CF_2Cl_2 were studied. A series of runs was made with M-1 tool-steel disk and rider specimens sliding in an atmosphere of CF_2Cl_2 at various ambient temperatures up to 1000° F. The results are presented in figure 7.

Friction of M-1 tool-steel specimens lubricated with CF_2Cl_2 showed two distinct levels. Between 200° and 400° F, the incremental influence of increasing temperatures was not established, so the two segments of the curve (fig. 7) are connected with a broken line. The higher friction coefficient is consistent with those reported previously for hard-steel specimens (refs. 5 and 12) at 75° F. Figure 7 shows that, at 400° F and higher temperatures, friction was very low (0.04). Similar friction was reported for a prepared iron chloride film in room-temperature experiments at high sliding velocities in reference 18. Both in the present data and in reference 18, the low friction could have resulted from melting of the iron chloride film. The melting point of ferric chloride is 570° F, and the reaction films are probably mixtures of various iron chlorides that could provide phases with a considerable range of melting points above 570° F. Frictional heat could easily cause surface temperatures that would melt such reaction films on bulk metal as cool as room temperature.

Friction data obtained at 1000° F with CF_2Cl_2 lubricating M-1 tool-steel specimens over a range of sliding velocities (fig. 8) further suggests the presence of a molten film of iron chlorides. The curve presented in figure 8 shows the same general form as the ZN/p curve commonly used to define the condition of hydrodynamic lubrication. Further discussion of this result is presented later in this report.

Figure 9 presents a photographic record of the appearance of several M-1 tool-steel specimens used in CF_2Cl_2 at temperatures up to 1000° F. Corrosion was greater at the high ambient temperatures. The corrosion problem becomes serious at temperatures of 600° F and higher with the steel parts in lubrication systems.

Chlorotrifluoromethane

Friction and wear data were obtained with CF_3Cl to determine whether higher ambient temperatures would make it possible to obtain effective lubrication with a gas containing less chlorine than CF_2Cl_2. Reduction of the amount of chlorine in the gas would be desirable in order to decrease corrosion.

Data obtained in runs with CF_3Cl are compared with data for CF_2Cl_2 (from fig. 7) in figure 10. The results at 75° F and at 1000° F show both friction and wear to be much higher with CF_3Cl than with CF_2Cl_2.

Corrosion was less at 1000° F with CF_3Cl than with CF_2Cl_2. The higher wear with the less reactive CF_3Cl suggests that at 1000° F corrosive wear is not the primary mode of wear. More effective film formation is necessary with CF_3Cl to obtain low wear.

Chlorotrifluoromethane Plus Sulfur Hexafluoride

About 1 percent by volume SF_6 was added to CF_3Cl to catalyze the formation of iron chloride on the M-1 tool-steel specimens. Friction and wear data were obtained at various temperatures from 75° to 1200° F. These data are presented in figure 11 (note that the wear data are plotted to a different scale than in fig. 7).

This mixture of CF_3Cl plus 1 percent SF_6 gave higher friction at both 75° and 1000° F than the CF_3Cl alone (fig. 10). The stable friction coefficient above 200° F was 0.27; this is higher than the values usually associated with effective boundary lubrication (<0.20). Wear with the gas mixture was lower at 75° F but higher at 1000° F than for CF_3Cl alone. The wear was relatively unaffected by temperatures up to 600° F. In all cases, however, wear was significantly higher than that reported for 1 percent SF_6 in CF_2Cl_2 in figure 13.

Corrosion was somewhat less with the CF_3Cl-SF_6 mixture (fig. 12) than with CF_2Cl_2 (fig. 9). At 1200° F there were appreciable differences in corrosion for the two gases. Because lubrication characteristics were not satisfactory, the reduced corrosive tendencies of CF_3Cl mixtures cannot be utilized.

Dichlorodifluoromethane plus Sulfur Hexafluoride

The benefits obtained with 1 percent SF_6 added to CF_3Cl, as de- 4989
scribed in the preceding paragraphs, suggested that the addition of SF_6 to CF_2Cl_2 might further improve its lubrication characteristics.

Run-in, as mentioned previously, was very important to the effective operation of sliding surfaces lubricated with reactive gases. One of the benefits of SF_6 additions to CF_2Cl_2 that was immediately apparent was that the run-in was less critical. An effective lubricating film was established, and low friction was obtained during the initial period of the run-in when 1 percent by volume SF_6 was present in CF_2Cl_2.

Friction at 75° F and 200° F (fig. 13) was slightly higher and somewhat more erratic than when CF_2Cl_2 alone (fig. 7) was used. The presence of iron sulfide in minute amounts could cause higher friction than iron chloride because of its greater shear strength. At all temperatures above 200° F, friction was as low or lower with the 1 percent SF_6 present. Wear values (fig. 13) were similar at 600° F, but significantly less wear was experienced at both higher and lower temperatures (the wear scale of fig. 13 is the same as in fig. 7, but different from fig. 11).

Corrosion with the gas mixture was similar to that obtained with the individual gases. Figure 14 shows photographs of specimens after operation at 75°, 600°, and 1200° F. The corrosion at 1200° F was extremely severe so that it was impossible to obtain significant wear data.

DISCUSSION

These experiments show the influence that several reactive gases and mixtures thereof used as lubricants have on the friction and wear of metal surfaces. The gases are considered to function as lubricants by forming sulfide or chloride films on the sliding interface of the metal surfaces. A summary of the relative wear obtained with the different gases at various temperatures is presented in figure 15.

CF_2Cl_2 and a mixture of about 1 percent SF_6 in CF_2Cl_2 gave very low friction coefficients (< 0.05) at temperatures above 400° F. It is suggested that a molten phase in the reaction film could account for the low friction. Of the probable reaction products, ferric chloride has the lowest melting point (570° F). Friction heat could cause temperatures higher than 570° F at the interface during runs made at room temperature. Reference 6 shows that temperature rises at 600° C (1112° F) are experienced with effectively boundary-lubricated metal surfaces. Friction trends showed discontinuities at temperatures between 200° and 400° F. Previous NACA experience, reported in reference 18, showed a similar discontinuity in room-temperature friction experiments made with a preformed ferrous chloride film at high sliding velocities. In the present experiments, the reaction film is considered to contain 15 to 20 percent ferric chloride, as suggested for direct iron-chlorine reaction in reference 17.

A series of runs made over a range of sliding velocities with 1000° F ambient temperature gave a trend of friction plotted against sliding velocity having the geometric form of a ZN/p curve commonly used in lubrication research to define the condition of hydrodynamic (thick fluid film) lubrication (ref. 19). These data strongly support the suggestion that a molten surface film is present at the sliding interface. This molten phase is undoubtedly extremely viscous, since previous data with liquid lubricants of very high viscosity (e.g., >762 cs at 100° F for water-soluble polyalkylene glycol) rarely showed hydrodynamic influence.

Results obtained with SF_6 alone showed appreciable data scatter at ambient temperatures around 400° to 800° F. A plausible explanation for these inconsistent data was found in the phase diagram for the iron sulfide system. Two crystalline forms of ferrous sulfide are of primary interest. At 138° C (282° F), the β form with a hexagonal crystal structure is transformed to the α form with a rhombic crystalline structure. The α form is stable to 298° C (568° F), but above that temperature a polymorphic transformation takes place and many allotropic forms develop. Crystalline structure is important in the shear resistance of a compound. It should not be surprising, therefore, that ferrous sulfide reaction films with a number of crystalline forms possible should give erratic behavior as a lubricant.

Corrosion of the bulk-surface area of M-1 tool steel was objectionable at 1000° and 1200° F with all the gases. Serious corrosion problems could exist with chlorine-substituted gases at temperatures as low as 600° F. It should be emphasized, however, that M-1 tool steel has been considered as a bearing steel primarily because of its hot-hardness characteristics. M-1 is very susceptible to oxidation corrosion and other forms of chemical attack. In the experiments reported herein, attempts to obtain effective lubrication with the less reactive (corrosive) gases were not successful with M-1 tool steel. Another approach to minimizing the corrosive problem is to utilize corrosion-resistant metals for slider surfaces.

Experiments showed that effective lubrication can be obtained by using a corrosion-resistant material for the rider specimen. At 600° F, SF_6 provided good lubrication for G-nickel and $7\frac{1}{2}$ percent silicon-nickel rider specimens sliding on M-1 tool-steel disks. The contribution of the silicon in useful alloys may merit close attention. It is of interest to note that, with oxides, silicon dioxide serves as a vitrification agent that lowers and extends the temperature range for softening. Lower interface shear strengths can result and would contribute to low friction and wear. Whether sulfides have similar characteristics is not known. 4989

The corrosion problem alone should not prevent the practical application of gaseous lubricants. With the proper selection of materials, gaseous lubrication is feasible at temperatures presently restricted to solid lubricants. The corrosion and wear tendencies observed with ferritic materials, however, indicate that high-temperature steel used in ball bearings may not be useful at high temperature with the gases of these experiments. A significant portion of the corrosion may occur as a result of deliquescence of the reaction products. Thus, a hermetically sealed lubrication system should be advantageous.

SUMMARY OF RESULTS

The boundary lubrication of metal surfaces with gases containing chlorine or sulfur was studied from 75° F up to 1200° F. The following results were obtained:

1. CF_2Cl_2 was an effective lubricant from 75° F to 1000° F. CF_3Cl was less effective than CF_2Cl_2. Extremely low friction coefficients at 1000° F (0.04) may have resulted from melting of the reaction film. Some evidence of a hydrodynamic effect further indicates the presence of a molten film.

2. A mixture of about 1 percent by volume SF_6 in CF_2Cl_2 had better lubricating properties than CF_2Cl_2 alone. The SF_6 was considered to act as a catalyst in chloride film formation.

3. SF_6 alone reduced wear appreciably but did not give low friction. A preformed sulfide film on tool steel had a beneficial effect on both wear and friction in both air and SF_6. Of the iron, copper, and nickel base alloys studied, the silicon-nickel alloys gave the best results. Rider specimens of a cast alloy of $7\frac{1}{2}$ percent silicon in nickel gave low friction (0.05) and wear at 600° F against M-1 disks with no preformed film.

4. M-1 tool steel and other ferritic materials were seriously corroded by the gases at temperatures as low as 600° F. Nickel alloys were not corroded noticeably in SF_6, although they were lubricated effectively.

5. Further studies are necessary to obtain corrosion-resistant alloys for slider surfaces that are capable of forming a lubricating reaction film. Other catalytic systems should also be studied.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, May 21, 1958

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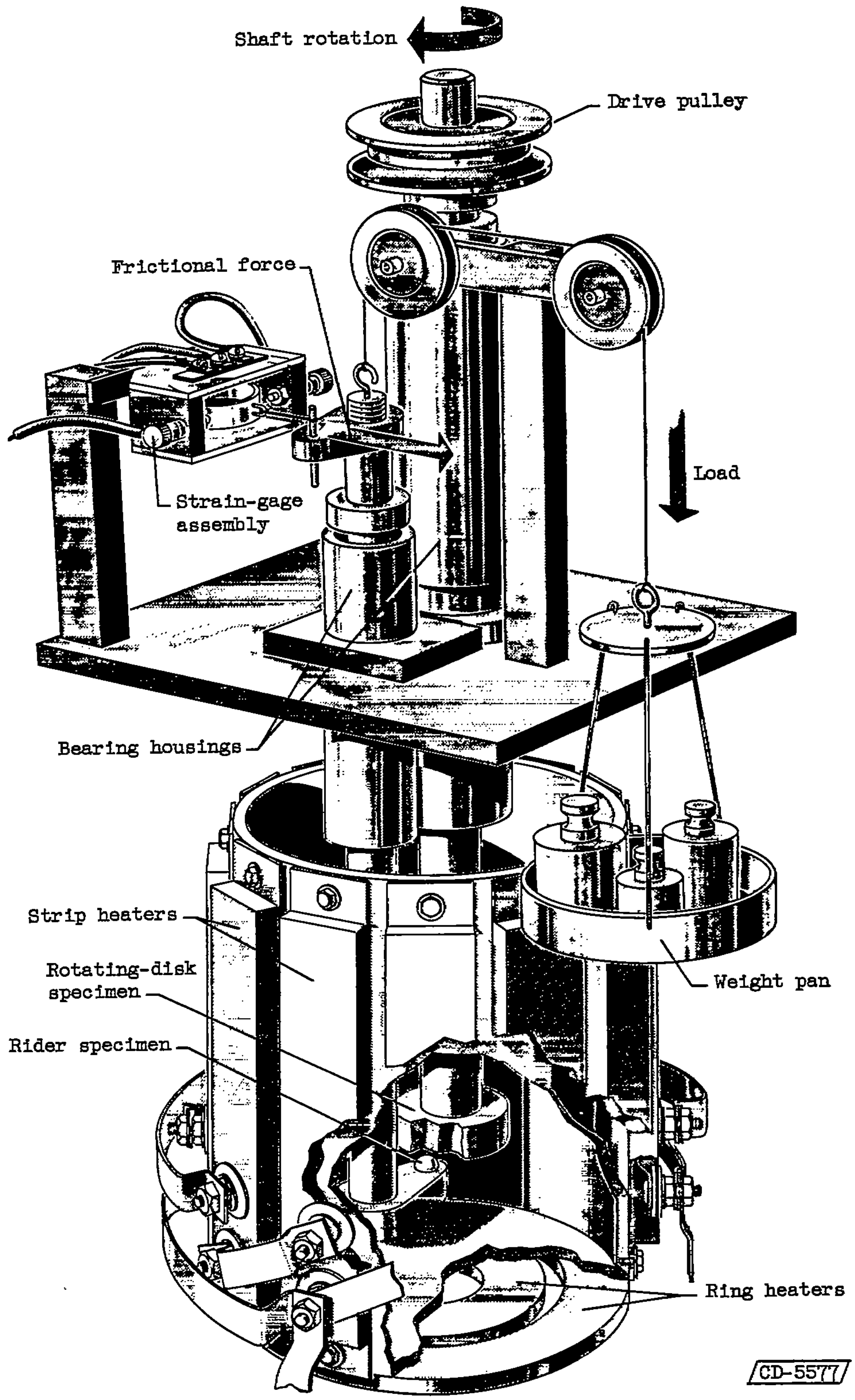

Figure 1. - Friction apparatus.

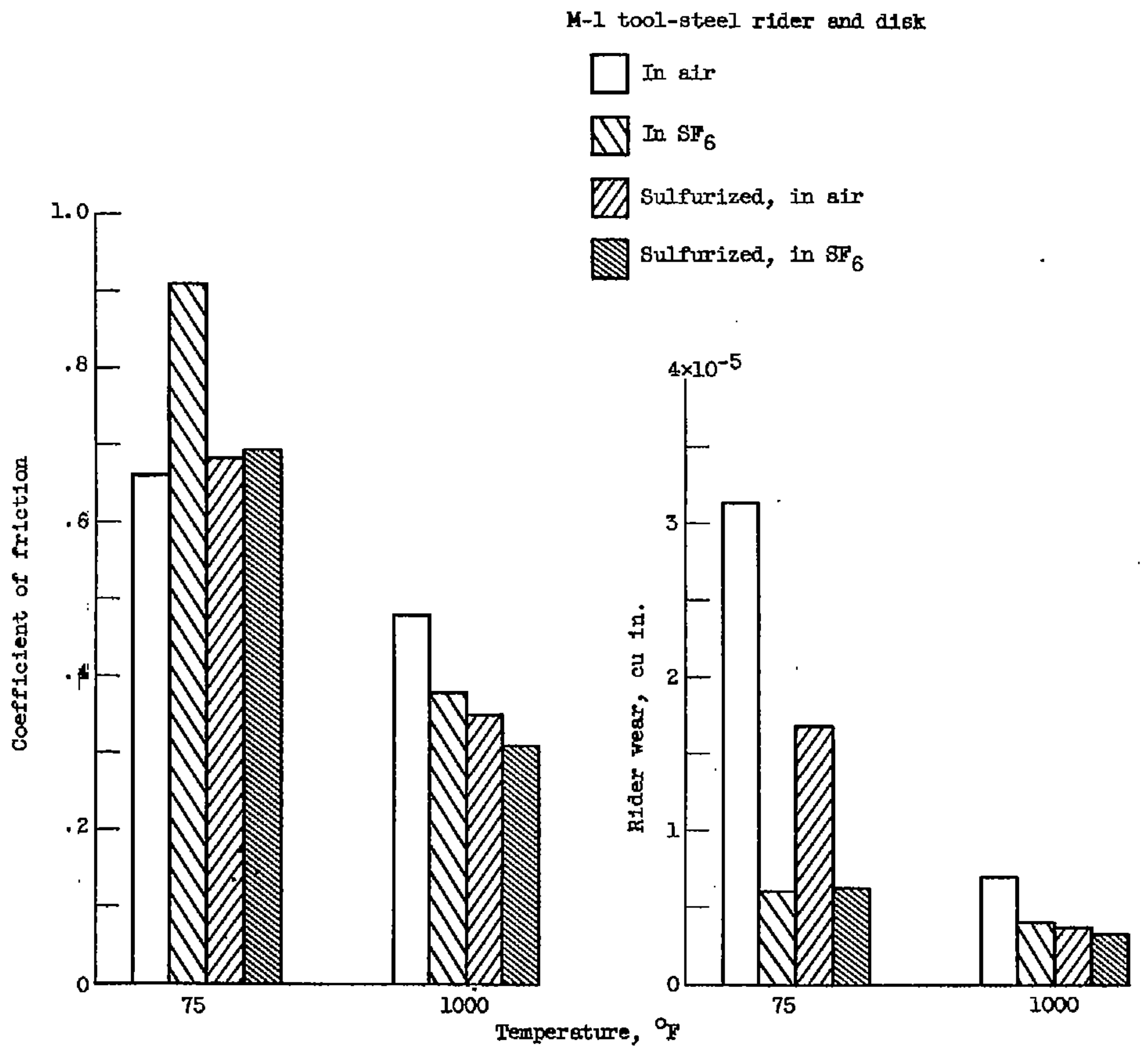

Figure 2. - Effects of sulfurizing on friction and wear of M-1 tool steel in air and in SF_6 lubricant. Sliding velocity, 120 feet per minute; load, 1200 grams; duration, 1 hour.

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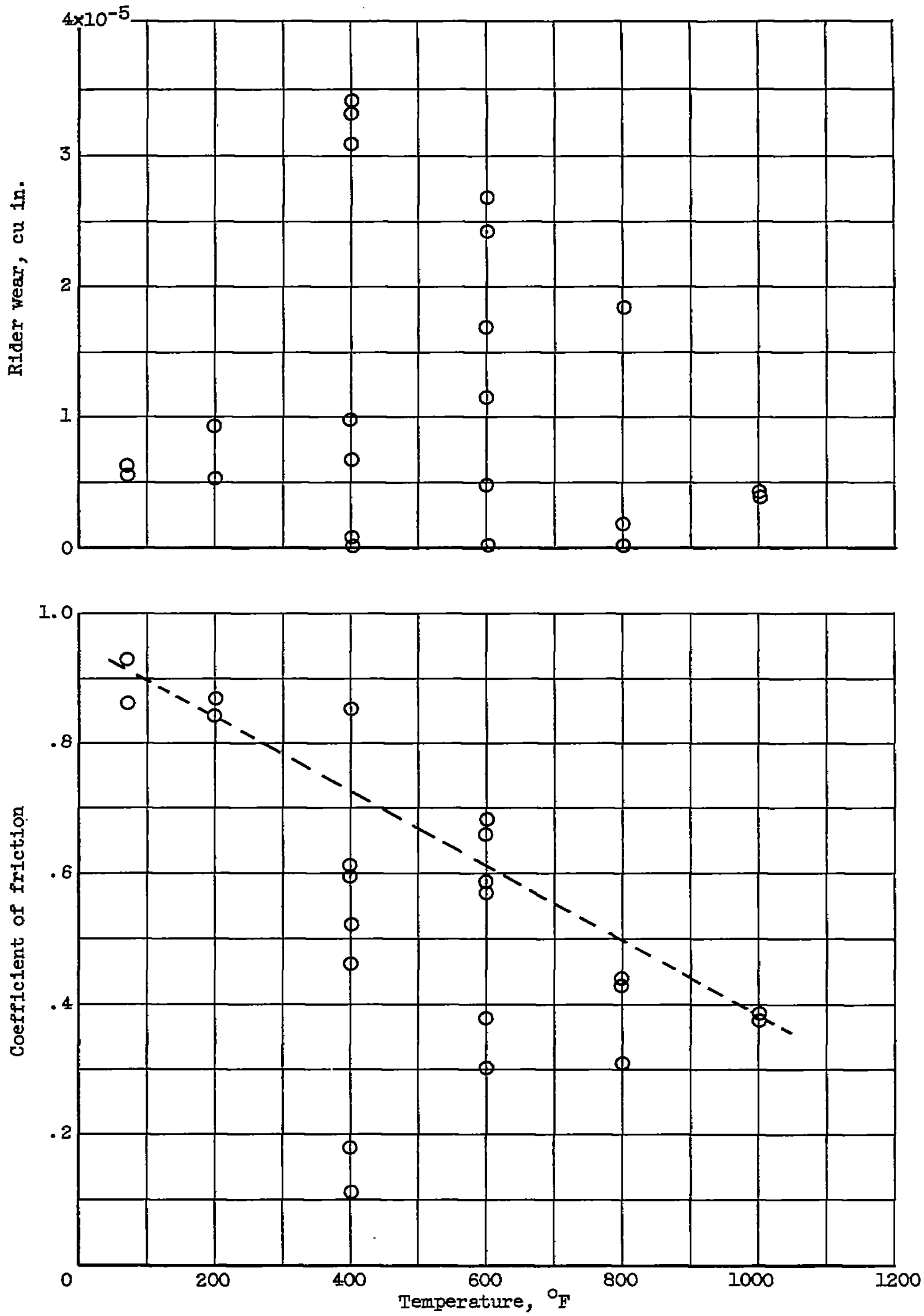


Figure 3. - Friction and wear of M-1 tool-steel rider on M-1 tool-steel disk at various temperatures with SF_6 lubricant. Sliding velocity, 120 feet per minute; load, 1200 grams; duration, 1 hour.

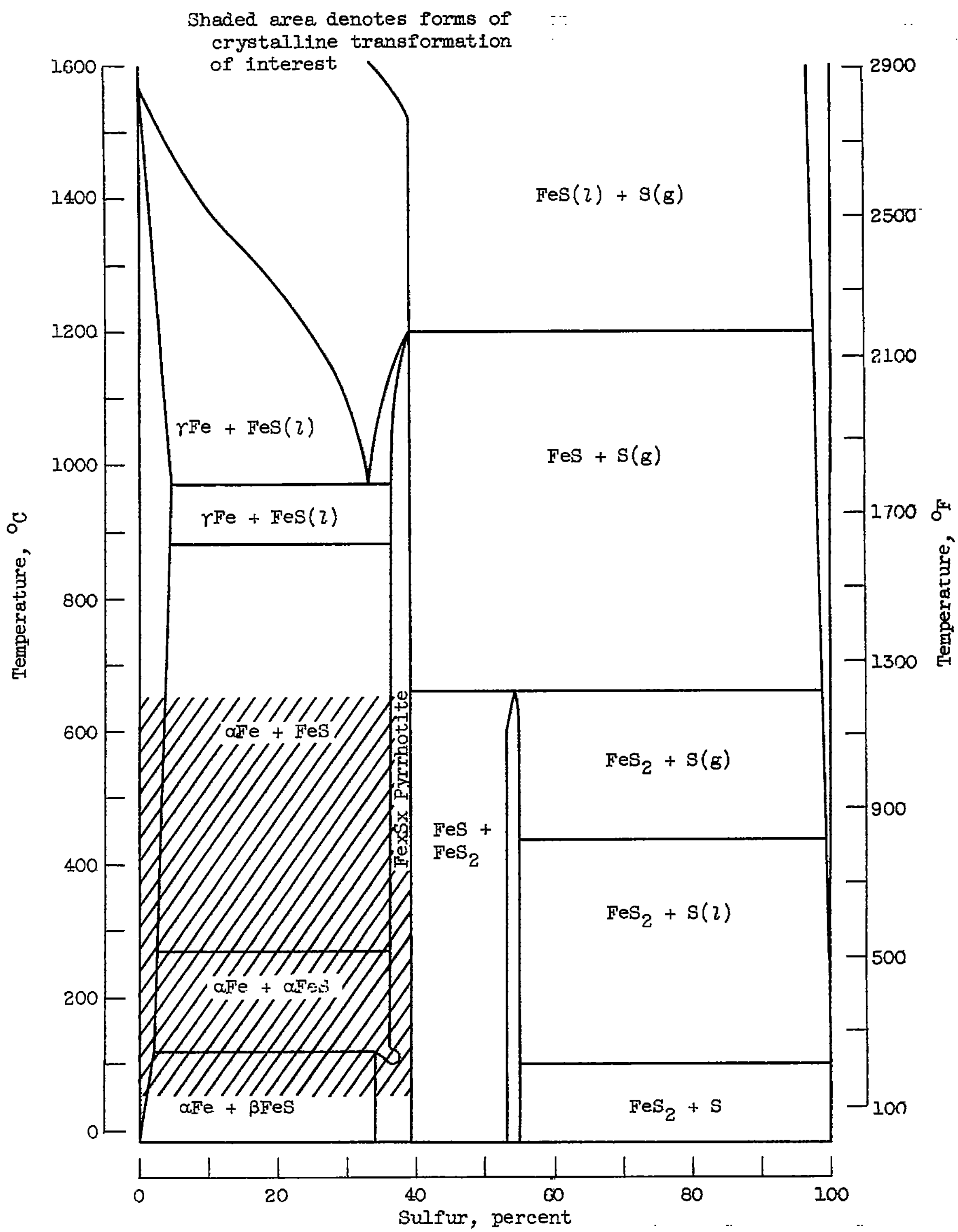
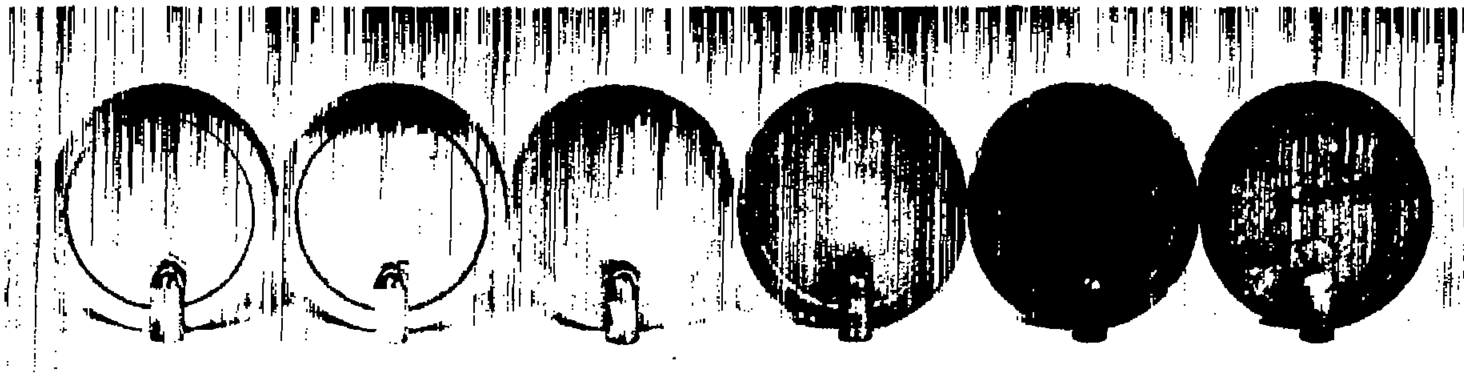


Figure 4. - Phase diagram of FeS system (adapted from ref. 17).



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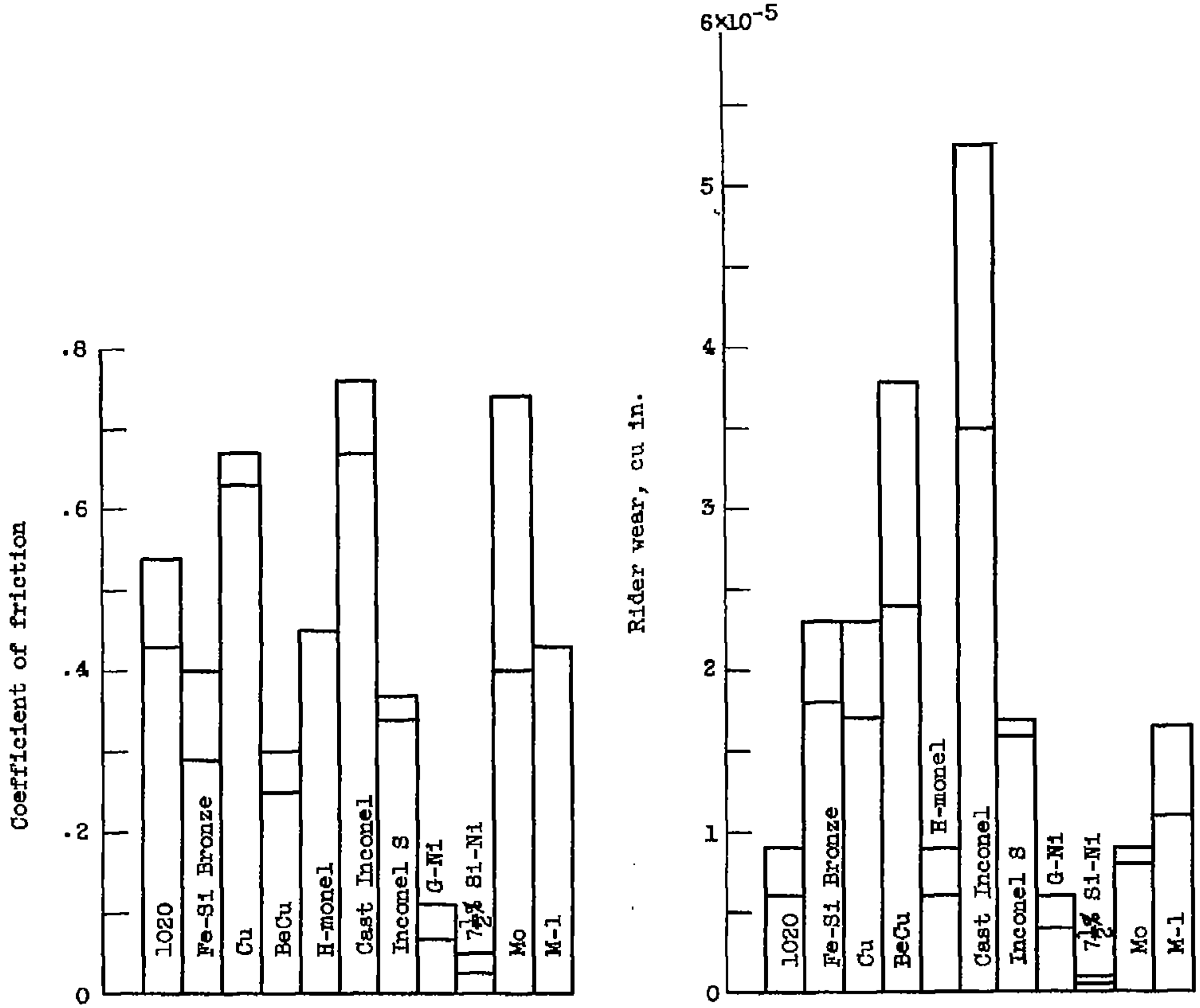
75° F 200° F 400° F 600° F 800° F 1000° F

Figure 5. - Photographs of corrosion on slider specimens after runs at various temperatures with SF_6 lubrication. Disk and rider specimens, M-1 tool steel; duration of run, 1 hour.



(a) Friction. (b) Wear.

Figure 6. - Lubrication of various rider materials run against M-1 tool-steel disks in SF_6. Sliding velocity, 120 feet per minute; load, 1200 grams; duration, 1 hour; temperature, 600° F.

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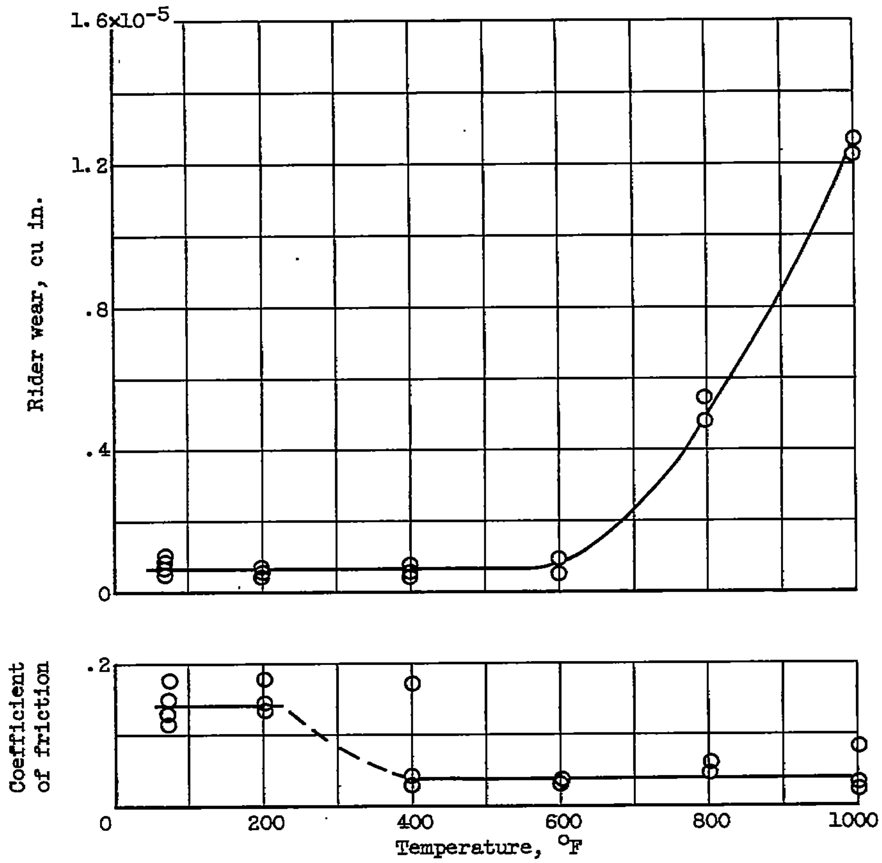


Figure 7. - Friction and wear of M-1 tool steel on M-1 tool steel at various temperatures with CF_2Cl_2 lubricant. Sliding velocity, 120 feet per minute; load, 1200 grams; duration, 1 hour.

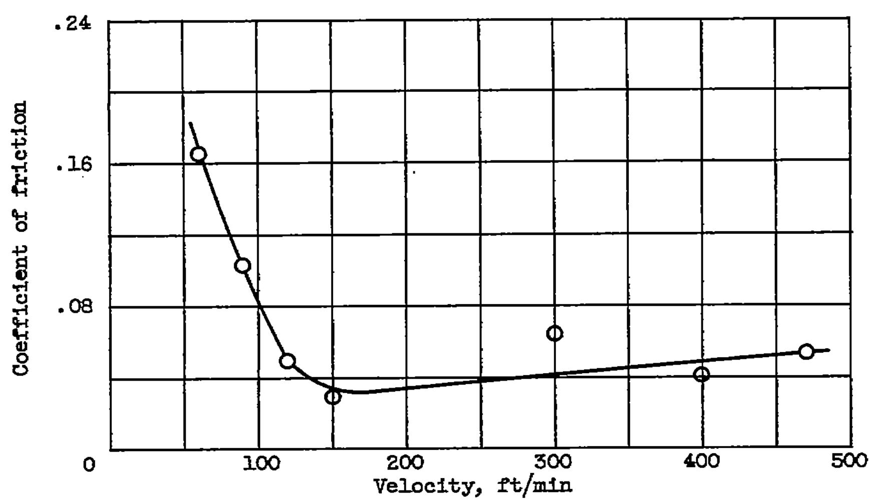
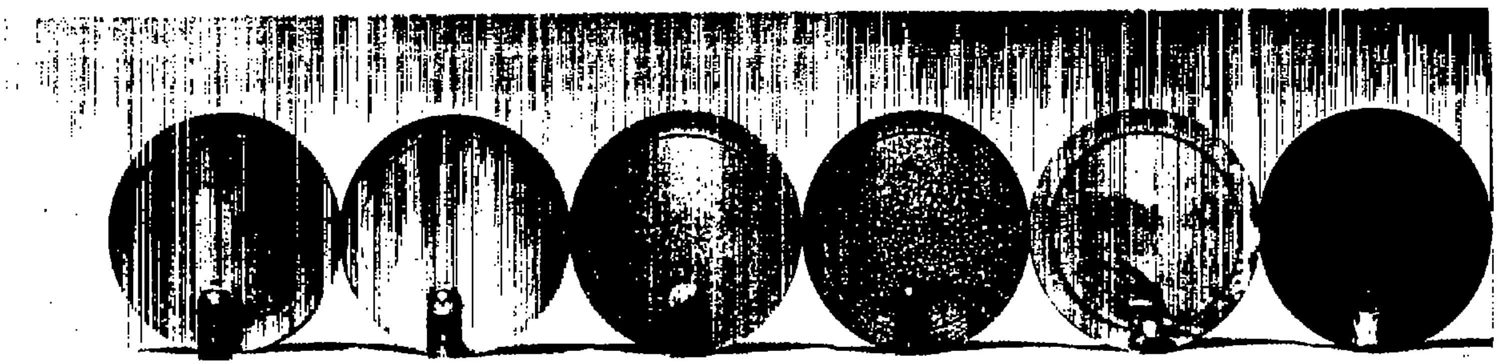


Figure 8. - Friction of M-1 tool-steel specimens with CF_2Cl_2 lubricant at various surface speeds. Load, 1200 grams; duration, 1 hour; temperature, 1000° F.



C-45835

75° F 200° F 400° F 600° F 800° F 1000° F

Figure 9. - Photographs of corrosion on slider specimens after runs at various temperatures with CF_2Cl_2 lubrication. Disk and rider specimens, M-1 tool steel; duration of run, 1 hour.

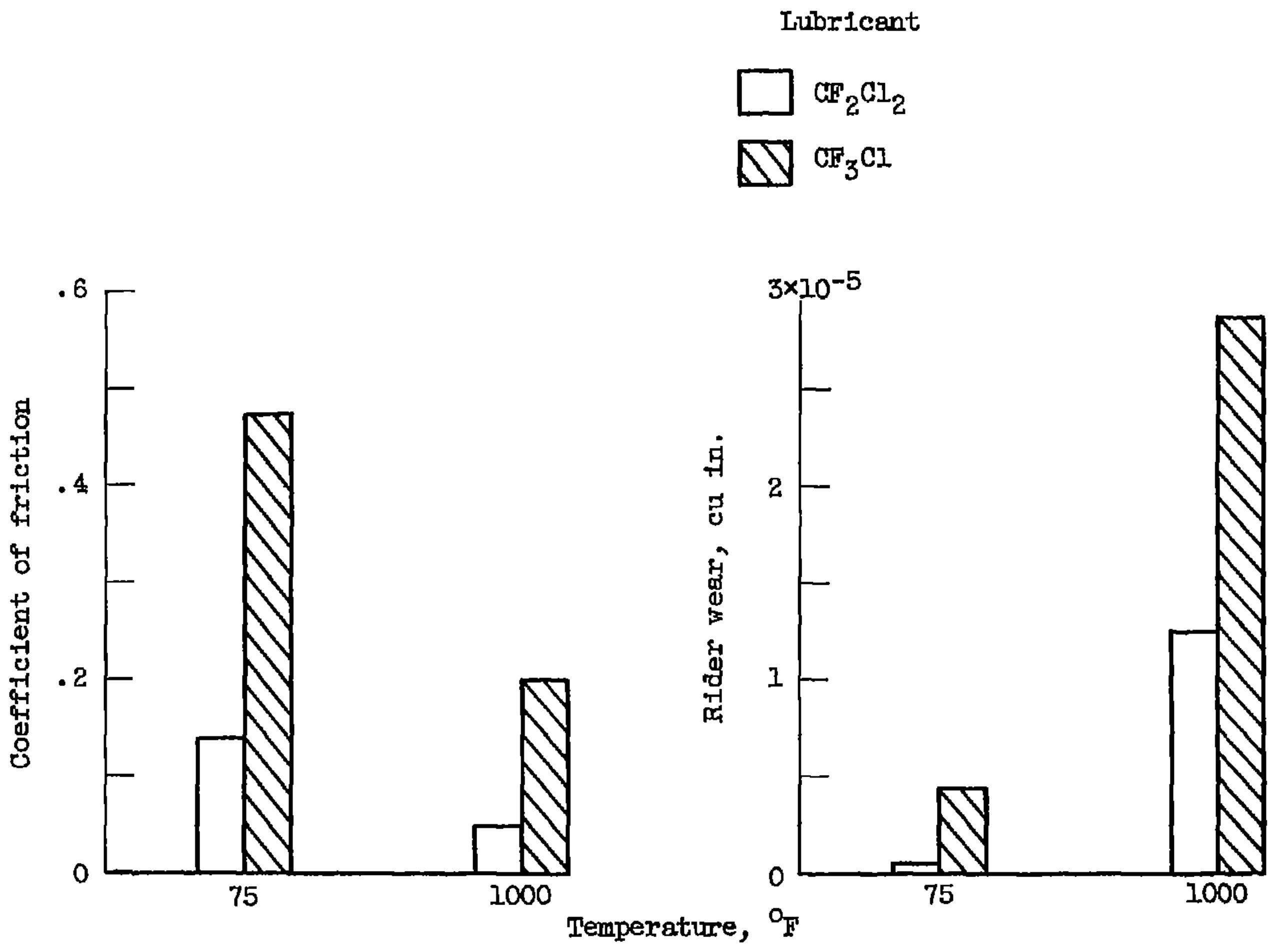


Figure 10. - Comparison of friction and wear of M-1 tool steel on M-1 tool steel in CF_2Cl_2 and in CF_3Cl. Sliding velocity, 120 feet per minute; load, 1200 grams; duration, 1 hour.

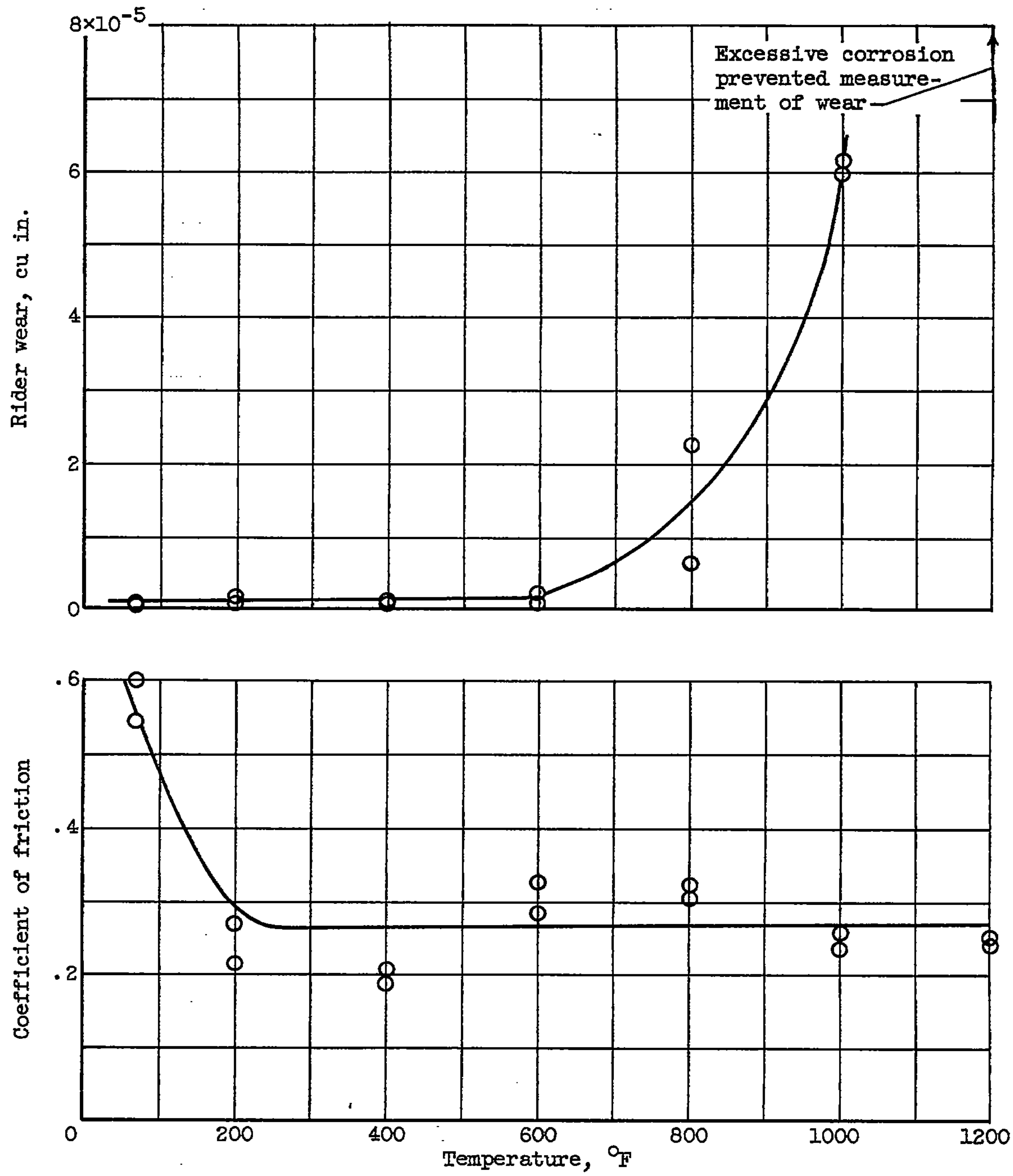
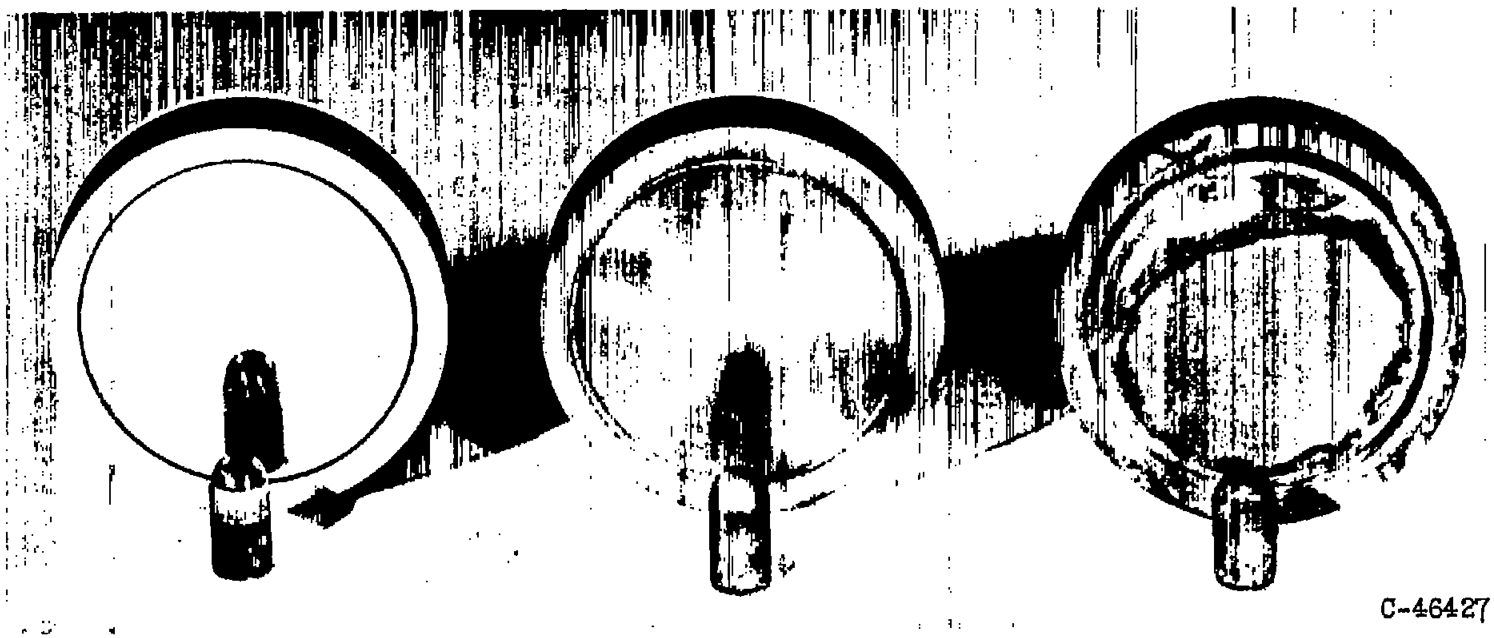


Figure 11. - Friction and wear of M-1 tool steel on M-1 tool steel at various temperatures with CF_3Cl plus 1 percent SF_6 as the lubricant. Sliding velocity, 120 feet per minute; load, 1200 grams; duration, 1 hour.



75° F 600° F 1200° F

Figure 12. - Photographs of corrosion on slider specimens after runs at various temperatures with CF_3Cl plus 1 percent SF_6 as the lubricant. Disk and rider specimens, M-1 tool steel; duration of run, 1 hour.

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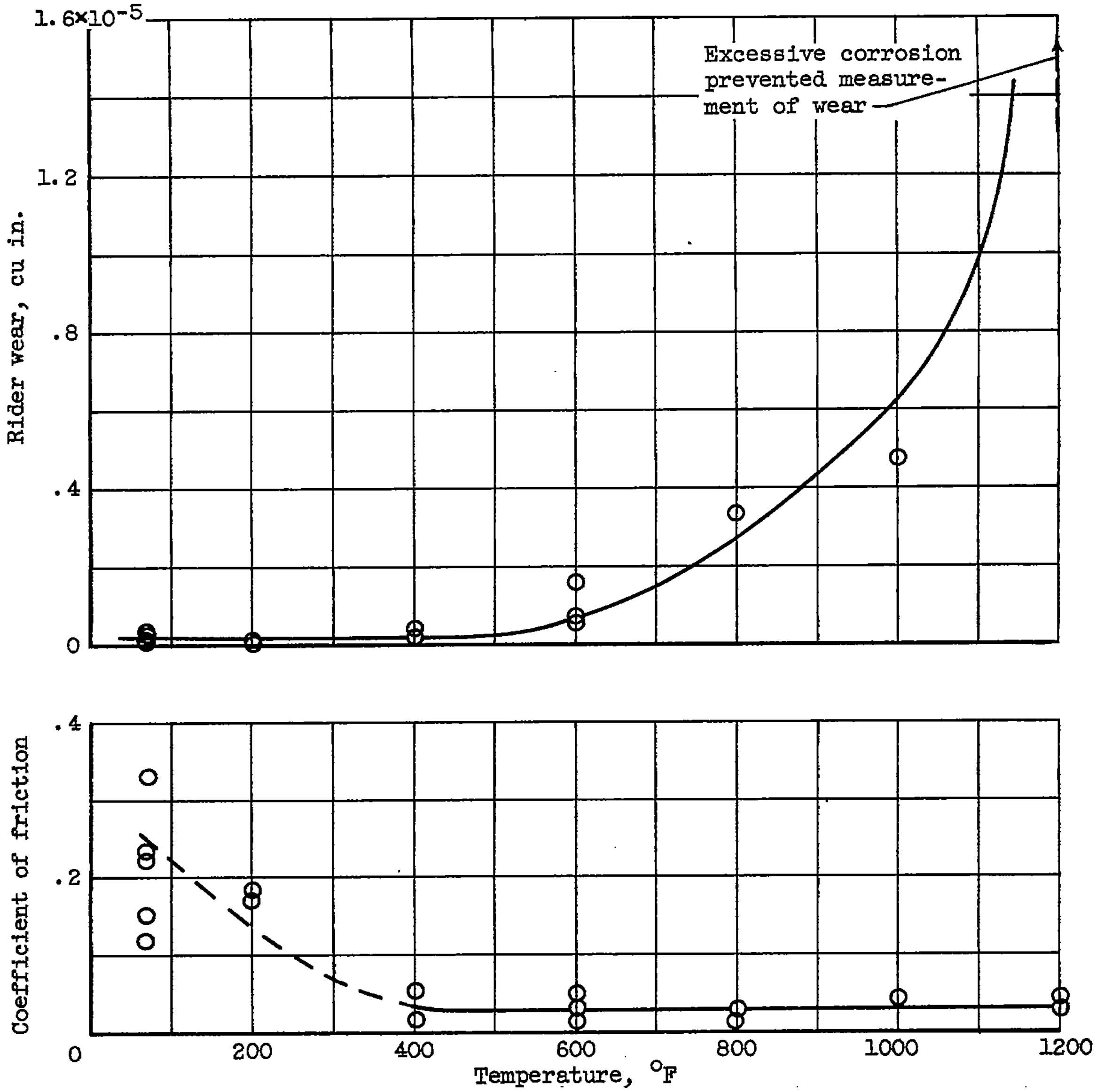
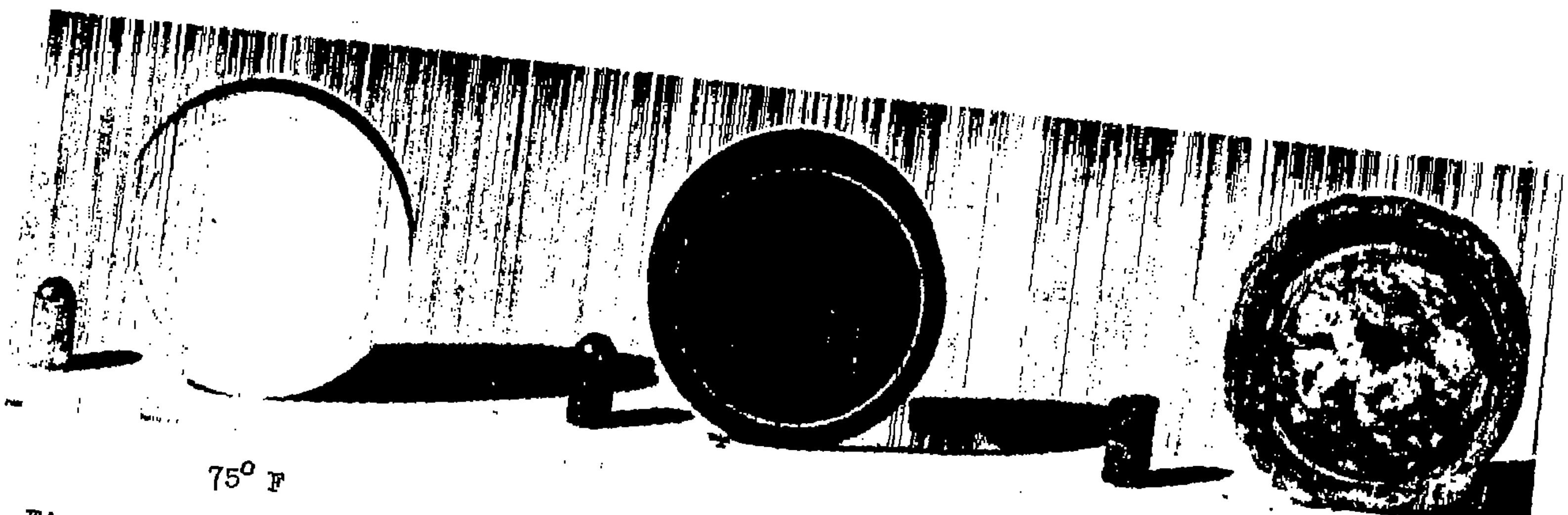


Figure 13. - Friction and wear of M-1 tool steel on M-1 tool steel at various temperatures with CF_2Cl_2 plus 1 percent SF_6 as the lubricant. Sliding velocity, 120 feet per minute; load, 1200 grams; duration, 1 hour.



75° F

600° F

1200° F

C-46048

Figure 14. - Photographs of corrosion on slider specimens after runs at various temperatures with CF_2Cl_2 plus 1 percent SF_6 as the lubricant. Disk and rider specimens, M-1 tool steel; duration of run, 1 hour.

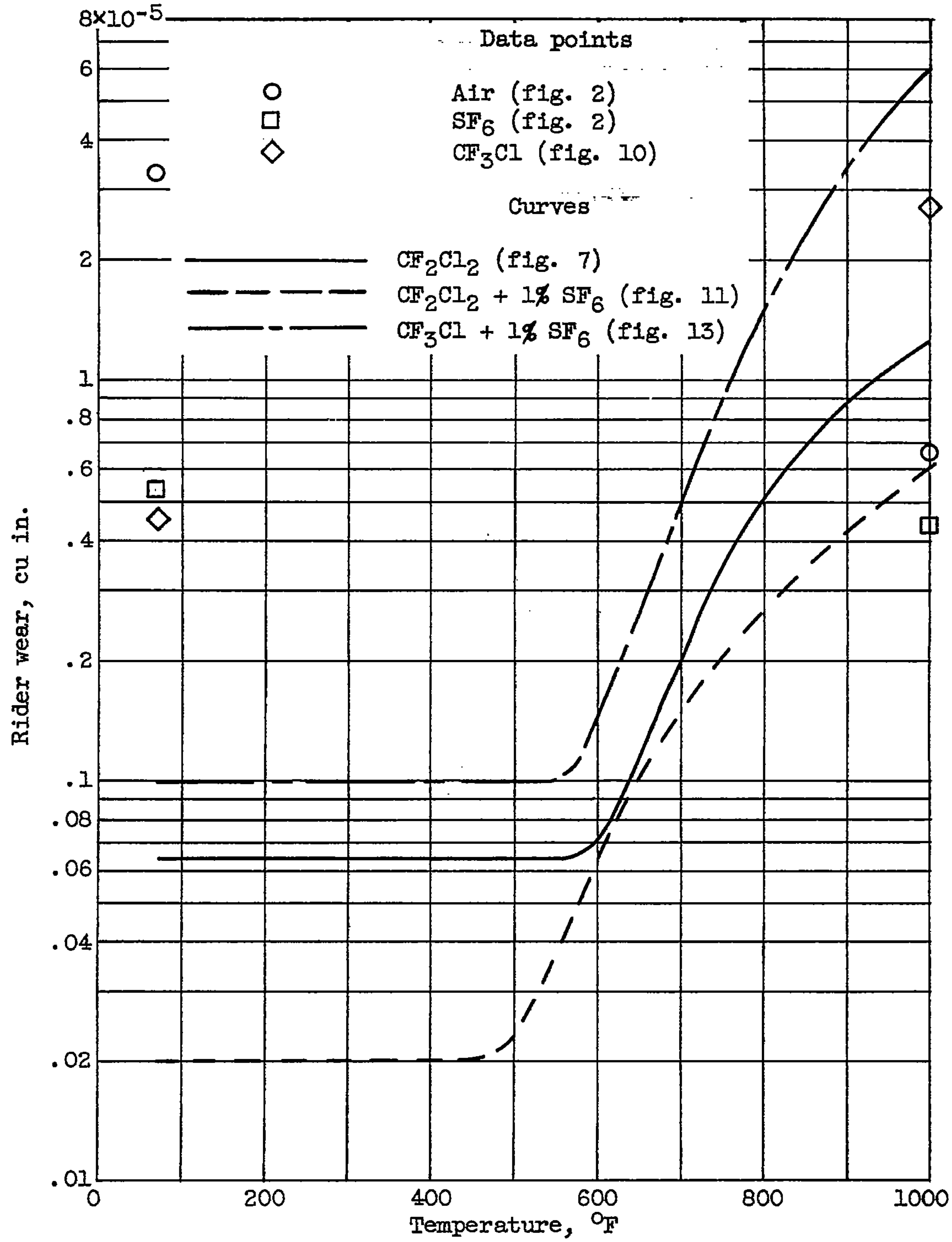


Figure 15. - Summary of wear using M-1 tool-steel specimens with reactive-gas lubricants at various temperatures. Sliding velocity, 120 feet per minute; load, 1200 grams; duration 1 hour.